TinkerTrap: A low-cost, customizable wildlife camera

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If you ask wildlife researchers what their most indispensable tool is, many will point to the camera trap—an automatic camera that quietly sits in the field for weeks, snapping pictures of passing animals. But today's commercial models, designed primarily for big-game hunters, cost more than $250 USD and are blind to smaller creatures, cold-blooded animals, and lack programmability for novel studies. To overcome this restriction, we're designing an open-source platform that packs the core functionality of a camera trap into a $50 USD development board, offering full control over triggers, timing, and add-on peripherals. We hope TinkerTrap will enable researchers—regardless of budget—to tailor deployments for unique species and behaviors.

I. Introduction

Camera traps, or motion-activated cameras, have become an essential tool for ecologists and other wildlife professionals. A typical commercial camera trap (CCT) combines a digital camera with a passive infrared (PIR) sensor in order to detect and capture images of passing animals. Mounted on trees or other natural supports for months at a time, camera traps are useful for detecting cryptic species, identifying species distributions, documenting predation, monitoring behavior, and estimating population sizes [1],[2].

Despite their widespread use in wildlife research, the CCT market has largely been driven by the needs of North American and European hunters [2]. Off-the-shelf units assume large, warm-blooded targets at fixed focal distances and users who rarely need to re-program the device. Consequently, most CCTs are:

- **Insensitive to reptiles, amphibians, invertebrates, and small birds** (poor thermal contrast).
- **Hard-wired** (limited to a single PIR trigger, no real-time clock (RTC) for scheduling, no additional sensors)
- **Expensive** (even "budget" models are ≥ $250 USD)

There is an increasing demand within the wildlife research community for a more flexible, customizable camera trap system that researchers can tailor to unusual species, behaviors, and environments [3][4],[5]. To meet this need, we started developing **TinkerTrap**: an open-source (OS) camera trap development board that reduces per-unit cost and exposes general-purpose input/output (GPIO) to support new peripherals and custom protocols.

II. Related Work

There have been some efforts by hobbyists and researchers to reverse-engineer CCTs. However, most of these devices rely on application-specific integrated circuits (ASICs), which are optimized for specific tasks and effectively hard-wired. As a result, researchers have resorted to creative workarounds—e.g. unscrewing the lens to shorten focal length or mounting traps opposite a cooler backdrop so a cold-blooded animal can trigger the PIR sensor—but these hacks void warranties and risk breaking expensive hardware.

More recently, the functionality of CCTs has also been enhanced through the use of machine learning and computer vision. Tools like MegaDetector automate the post-processing task of detecting and classifying species in images, significantly reducing the labor required for manual labeling. ConservationXLabs has gone a step further by enabling real-time image analysis and edge detection on CCTs. They get around the inflexibility of CCTs by using Sentinel, a GPU-powered computer that attaches to a CCT's SD card slot and intercepts and processes images directly from the SD card. While beneficial, neither solution fixes the underlying rigidity of the CCT itself.

As accessibility to OS hardware has increased, and with impressive processing power now available at low cost, electronic prototyping platforms (EPPs) offer the potential to provide researchers with complete control over imaging procedure, compatibility with multiple sensors, and access to wireless communication. Several innovative solutions based on Arduino and Raspberry Pi have appeared [6],[7]. Though each offers some added functionality over CCTs, they overlook fundamental requirements in cost, usability, and battery life, preventing their broader adoption. To date, there is still no open-source camera trap platform to have seen widespread adoption within the wildlife research community.

III. Proof-of-Concept

Our overarching aim is to replicate for camera trapping what AudioMoth [8] achieved for passive acoustic monitoring: a field-worthy, open-hardware device that surpasses commercial offerings while preserving ease of use. We identified three design targets to be particularly critical to a impactful design: (i) a per-unit price below $50 USD, (ii) a minimum battery life of eight weeks under typical imaging conditions, and (iii) a trigger-to-capture latency under 0.5 s so that fast-moving animals are not missed.

Meeting these requirements depends strongly on the underlying microcontroller. We selected Espressif's **ESP32** system-on-chip (SoC) because it combines low-power deep-sleep modes, an extensive open-source software ecosystem (spanning the Arduino core, ESP-IDF, and MicroPython), and on-chip Wi-Fi/Bluetooth offer additional future capabilities (i.e., data off-load, over-the-air updates, and battery checking).

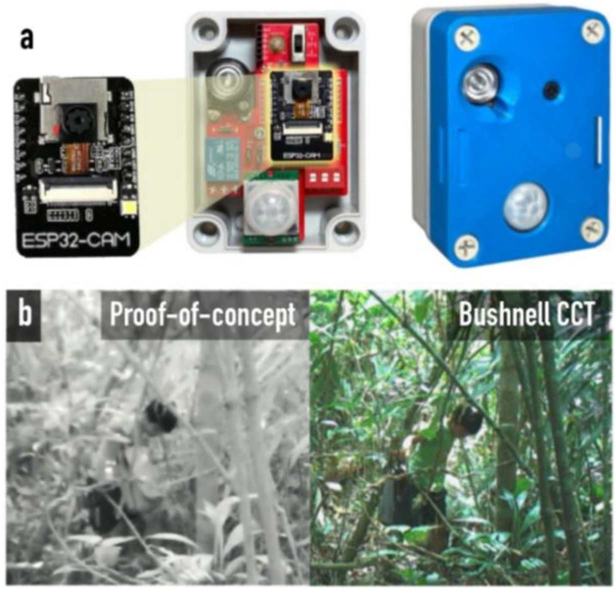

Fig. 1. TinkerTrap proof-of-concept. (a) ESP32-CAM and custom shield fit in a 3D-printed enclosure. (b) Field test comparison between proof-of-concept and a conventional CCT (Bushnell).

The initial proof-of-concept, completed in 2021, combined an off-the-shelf [ESP32-CAM](ESP32-CAM) module with a custom two-layer shield and a weather-sealed, 3D-printed enclosure (Figure 1a). In a batch of ten units the bill of materials averaged $42 USD. The shield broke out the ESP32-CAM's available GPIO to a header for a HC-SR501 PIR module or an alternative trigger source. A single 850 nm IR LED provided illumination, while a 5V relay enabled control of external loads such as higher-power LED arrays or acoustic deterrents. Table 1 provides a subsystem breakdown for this prototype as well as targets for the next revision.

Four units were deployed for a two-week field trial at the Fincas las Piedras Biological Station in Peru (Figure 1b). All devices booted and detected motion, capturing 654 images at 5 MP resolution. The fastest trigger latency measured ex-situ was 0.7 s, but an additional 0.5 s delay was added in firmware to allow the OV5640 auto-exposure routine to stabilize, so effective latency in the field was ~1 s. Deep sleep current measured roughly 3 mA, limiting four AA cells to a projected five-week battery life. At night, the single IR LED failed to sufficiently illuminate scenes, and during the day, the absence of an IR-cut filter (IRC) resulted in pronounced color shifts. The prototype also lacked a real-time clock (RTC), preventing precise time-stamping, and sparse on-board logging made it difficult to diagnose intermittent dropouts or corrupted images.

TABLE I. PROTOTYPE COMPONENTS

Subsystem	**Prototype 1**	**Prototype 2**
MCU	ESP32-S (ESP32-CAM)	ESP32-S3-WROOM/-MINI
Optics	OV5460 + fixed IR-pass lens	OV5460 + IR-cut solenoid
Illumination	Single 3W 850nm LED	LED array, 3A FET driver
Timekeeping	40 MHz internal crystal (±50ppm)	DS3231 RTC (±2 ppm)
Trigger	Adafruit PIR Module (BIS0001 + RE200B)	On-board PIR (EKMB1307113K)
Daylight sensing	---	LDR analog input
IR-cut mechanism driver	---	H-bridge (low-side dual MOSFET)
Configuration	Firmware	JSON config file on SD card
Programming	External FT232RL USB-UART	On-board USB bridge

IV. PLANNED REVISION

Work on TinkerTrap picked up again this year with the goal of fixing the issues we saw in Peru while moving from a proof-of-concept shield to a stand-alone development board. Remaining within the Espressif ecosystem keeps parts inexpensive and the development tools familiar, but it also means working close to the limits of the hardware. More recent camera development boards such as the [ESP32-S3-EYE](ESP32-S3-EYE) and the Adafruit Memento show that this trade-off is workable: they stream JPEG, log to micro-SD, handle battery charging, and include USB-serial bridges, albeit with little GPIO to spare. The ESP32-S3 SoC should suffice, with firmware and added hardware addressing specific shortcomings of the first build.

The hardware plan is to adopt the proven topology of the ESP23-S3-EYE, while removing unnecessary features like the LCD display, accelerometer, and multiple push-buttons. Reclaimed GPIO will be reallocated to an external RTC for timestamping and timed wake-ups, an H-bridge driver to flip an IRC solenoid, a LED driver, an onboard PIR sensor, and a light dependent resistor for light level sensing. If additional pins are desired, an I^2C port expander, as used on the Memento, can be included. Table 1 lists the full subsystem plan.

Because a full four-layer board still presents a challenging commitment, we are considering starting development with a preliminary half-revision: an expansion board that plugs into the headers of the ESP32-S3-EYE. This system is block diagramed in Figure 2. The expansion board will carry the RTC, solenoid driver, PIR, LDR, and LED array. It may require a redundant buck converter to power the solenoid and LED array, but this configuration should still be useful to validate power budget, trigger latency, and image quality. Component selection, schematic design, and firmware work are currently under way. Once parameters are verified and functionality tested, the expansion and main board schematics will be combined into a single board.

Several design choices are still on the table—how to reduce standby power further, whether to power with conventional AA's or move to a rechargeable lithium-ion, and how to design for maximum usability. Additionally, final assembly will require fine-pitch, leadless packages on both sides of the board, something that would prove difficult in our current workspace. The pro² summer school offers an invaluable opportunity to advance this project, providing hands-on guidance in prototype development and device production while connecting with fellow makers and researchers.

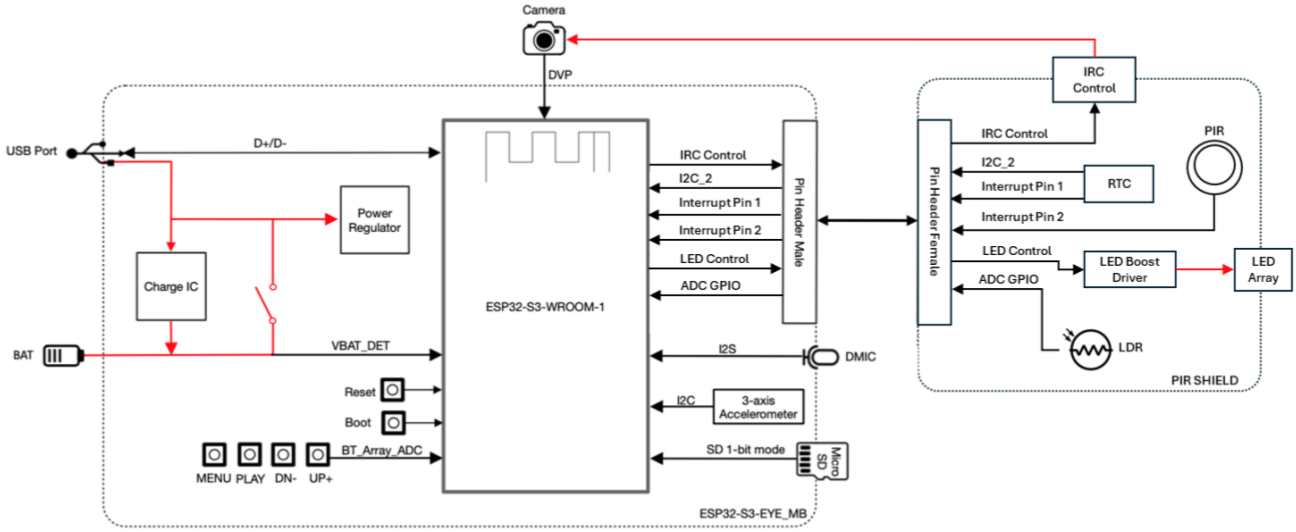

Fig. 2. Block diagram of the ESP32-S3-EYE and proposed expansion board.

V. Responsible Innovation

By letting users swap sensors, adjust capture protocols, and log additional variables (e.g., temperature or light), the TinkerTrap platform can be repurposed for questions that commercial camera traps rarely address. This flexibility extends the platform beyond typical target species and enables entirely new kinds of studies. This may help fill gaps in biodiversity data at a time when detailed, species-level information is urgently needed. Additionally, an open-source design lowers the entry cost, lets users repair and modify their own equipment, instead of relying on expensive and single-purpose tools. After the prototyping phase, we would like to launch a GroupGets campaign similar to the one used for AudioMoth [9]. A group-buy lowers per-unit cost, streamlines international shipping, and fosters a user community that can share their customization and field experience. By lowering these barriers, we hope to encourage community participation in wildlife study, from backyard surveys to rainforest monitoring.

VI. Author Bios

Ben Seleb: I am an engineer with a long-held passion for biology and conservation. As an undergraduate, I co-founded *Tech4Wildlife*, a research course that paired engineering students with conservation partners to provide technological solutions. After graduation, I helped launch an ag-tech startup, developing drone systems for long term cattle monitoring. Now, as a PhD candidate in Quantitative Biosciences at Georgia Tech, my work spans coding, hardware prototyping, and field deployment. I've built triggering equipment to collect high speed video of multiple species, designed and assembled PCBs as part of my lab's low-cost hearing aid initiative, and built custom biologgers to study sled dog biomechanics and collective behavior.

Saad Bhamla: I am a biomechanist focused on the intersection of biology, physics, and engineering to create knowledge and tools that inspire curiosity and innovation. I believe that understanding biomechanics across species can lead to transformative inventions, especially in the realm of ultra-low-cost devices for global health. As an inventor, I have developed several notable low-cost devices, including a paper centrifuge, a low-cost electroporator, and a low-cost hearing aid. My contributions have been recognized with numerous early career awards. I served as the Principal Investigator on this project in our lab at Georgia Tech, contributing to technical feedback, overall project management, and funding for this project.

VII. Acknowledgements

This work was originally supported by Saad's startup grant (2020-2021), and has since been progressed as a side project. Initial prototypes were tested alongside our collaborator's (Dr. Geoff Gallice, Alliance for a Sustainable Amazon) ongoing CCT study (Fig 1b) at Fincas las Piedras, Peru.

VIII. References

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